Implications of Phosphor Coating on the Thermal Characteristics of Phosphor-Converted White LEDs

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Abstract— The phosphor layer in phosphor-converted white Light Emitting Diodes (pcLEDs) affects their optical and thermal performances. This paper reports the effects of phosphor thickness and particle concentration on the optical efficiency and temperature rise on conformal phosphor-coated LED package. It is observed that a thicker phosphor layer and a higher phosphor particle concentration will increase the amount of backscattering and back reflection of light from the phosphor layer. These light extraction losses not only reduce the optical efficiency of the light output but also cause heat accumulation in the phosphor layer, leading to higher LED junction temperature. At 2700 K correlated colour temperature (CCT), the temperature rise is observed to increase by as much as 2.6 times as compared to its blue emitting LED package. However, the self-heating effect can be reduced through its die-bonding configuration. Structure function-based thermal evaluation shows heat accumulation in the phosphor layer and that flip-chip bonding can dissipate the heat generated in the GaN LED and phosphor layer effectively. Evidence in this study demonstrates that optical efficiency and thermal resistance of pcLEDs are dependent on the CCT ratings.

***Index Terms*— heat generation, Light emitting Diodes, phosphor, Thermal resistance**

I. Introduction

ADVANCES in cost-efficient phosphor coating technologies and high color rendering index (CRI) emitter materials have led to the widespread adoption of phosphor-converted light emitting diodes (pcLEDs). The most widely used and commercially available pcLEDs is based on an InGaN LED chip with the Yttrium Aluminum Garnet: Cerium (YAG:Ce) phosphor. The phosphor host emits yellow light (photoluminescence) due to the excitation of blue light (electroluminescence) from the InGaN LED chip, and the mixing of the blue and yellow light produces white light. By altering the properties of the phosphor layer, such as thickness, concentration and location etc, a wide range of CCT values can be realized. The thickness and concentration of the phosphor layer as well as the phosphor particle size are found to strongly influence the luminous efficacy and the color chromaticity and CRI of the light emitted. Tran et al. [1] demonstrated that the lumen output can be improved by regulating the phosphor layer thickness and concentration of phosphor particles in the phosphor layer. Backscattering and back reflection of light can also be minimized by employing optimally sized phosphor particles [2, 3]. To understand the optical efficiency and its ensuing thermal evaluation, it is important to analyze the radiant energy emitted from the LED package.

These optical losses bring upon the implication of phosphor self-heating effect [4-7] which may exacerbate the package's thermal load and as a result, reduce the optical light output further. Huang and Yang [4] have shown that 25% to 45% of the radiant energy emitted from the LED chip is lost as heat during the process of down converting high energy blue light into relatively lower energy yellow light. The heat generated by the phosphor particles not only increase the junction temperature of the LED device, but may also cause phosphor quenching. This will inevitably lower the optical efficiency and may raise thermal issues that could cause materials degradation. Lago et al. [5] reported significant temperature rise on remote phosphor plates under blue light irradiation. Simulations on the optical-thermal interactions in the phosphor particles were also conducted to understand the phosphor self-heating effect [6, 7]. The temperature on the phosphor layer is found to be significantly higher than the LED junction temperature and this changes the photometric and colorimetric properties of the white light emitted. Although it is recognized that the phosphor particles generate self-heating, its implications on package-level thermal performance have not been well understood. Heat generation in the phosphor layer should be taken into consideration in the packaging design to improve the phosphor's conversion efficiency and prevent abrupt emitter failure.

In this paper, the optical performance and thermal response of the LED package will be evaluated under various phosphor

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layer variations as well as die-bonding configurations. Through understanding the implications of light extraction losses in the phosphor layer on the thermal performance of a package, the performance and reliability of high power pcLED packages can be improved.

II. Experimental Setup and Procedures

A commercial 1mm^2 GaN LED, with a blue peak wavelength of ~450 nm, is bonded onto AlN substrate either conventionally or in a flip-chip approach. In the conventional die-bonding approach, the GaN LED is grown on a 100 µm sapphire substrate and is subsequently bonded onto AlN substrate. In the flip-chip bonding configuration, the GaN LED is bonded directly onto an AlN substrate via Au bumps. For both bonding configurations, a layer of phosphor is subsequently coated over the LED chip to emit white light. The thickness of the phosphor layer in conventional bonded LED and the concentration of phosphor particles in flip-chip bonded LED are varied to obtain different CCT values. Table I shows the phosphor thickness variation for different LED die bonding configurations. To achieve 2700 K CCT, Lutetium-based phosphor particles are used while the others use YAG-based garnet phosphor particles. Lutetium-based phosphor has better CRI properties whereas YAG-based phosphor exhibit higher efficiency [8, 9]. The elemental composition of the Lutetium-based phosphor particles is Lu (61-62 wt.%), Al (14-16 wt.%) and O (22-24 wt.%) while the YAG-based phosphor particles have average compositions of Y (42-49 wt.%), Al (15-21 wt.%) and O (30-35 wt.%).

TABLE I
Phosphor Thickness Variation for Different CCT Values and Die-Bonding Configurations

Die-Bonding Configuration	CCT (K)			
	2700	4000	5000	7000
Conventional (C)	95 µm	85 µm	48 µm	32 µm
Flip-chip (FC)	60 µm			-

To understand the implications of the phosphor layer in the package, absolute optical and thermal properties of each LED packages are evaluated. To compare the thermal behavior of the die-bonding configuration, the normalized performances of the LED packages were evaluated.

These LED packages are measured using an integrated LED measurement system. The system consists of a Labsphere 20" integrating hemi-sphere system, a Keithley 2602A Source Meter, a Mentor Graphics T3ster, and a Peltier-based temperature controller (TEC). The LED is secured onto a temperature-controlled surface with an accuracy of up to 0.1 °C. The photometric and colorimetric properties of the emitted light output are measured using a spectro-radiometer. To ensure traceable optical measurement, reference lamp calibration and absorption correction were conducted prior to each measurement. Thermal measurement, which includes LED junction temperature T_j and transient thermal response, are approximated by means of the electrical forward voltage V_F of the LED. The temperature coefficient of the forward voltage is ~1.4 mV/°C and its high sensitivity with temperature provides accurate junction temperature measurement. The time-dependent behavior of the heat flow path in the LED packages are analyzed using the structure function-based evaluation of the thermal transient measurements. Thermal resistance R_{th} is usually calculated from the change of temperature rise ΔT_r in a package under a fixed applied heat input power P_H. Since optical light radiation is emitted out of the LED, the remaining heat dissipated power is thus determined by the difference between the supplied electrical input power and the optical radiant output. The total radiant flux emitted from the LED is factored into consideration for the calculation of the real thermal resistance, $R_{th\text{-}real}$. Electrical I-V measurement is conducted prior to and after the optical-thermal measurements to ensure that device does not degrade significantly during testing.

III. Results on the Thermal Characteristics

A. Photometric Properties

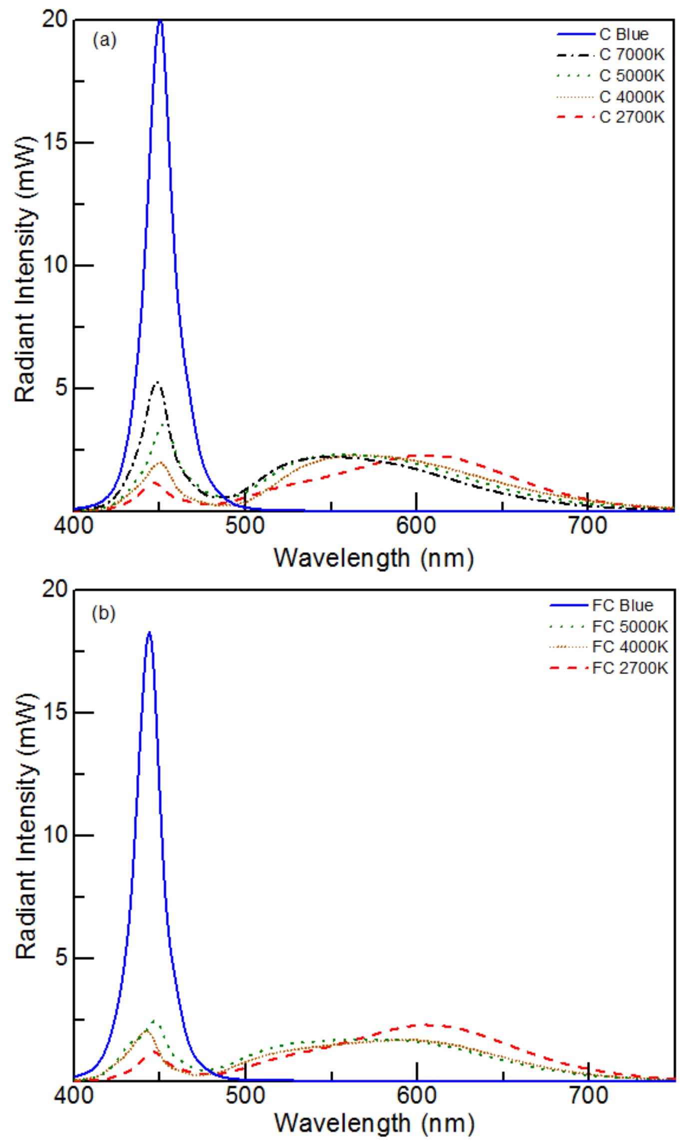

Fig. 1. Typical spectral power distribution of (a) conventional and (b) flip-chip bonded LEDs at different CCT rating.

The spectral power distribution (SPD) characteristics of the blue and pcLEDs are shown in Fig. 1. Both sets of LEDs exhibit a blue peak emission of ~450 nm at 20 °C. After phosphor is deposited over the LED, the blue peak intensity reduces significantly and a broad yellow-orange spectrum is produced. Depending on the CCT rating, different proportion of blue and yellow light is acquired. As the CCT value decreases, the blue peak intensity will reduce while the yellow-orange spectrum broadens and shifts to longer wavelength accordingly. This shows that a higher proportion of down-conversion processes occurring in the phosphor particles increase the yellow-orange spectral intensity. From the SPD characteristics, the efficiency of the blue and pcLEDs are subsequently evaluated at various operating temperatures. The conventional bonded LEDs exhibit a high external quantum efficiency of ~43% at 20 °C and reduce steadily with higher operating temperature. On the other hand, flip-chip bonded LEDs have a lower efficiency of ~39% at 20 °C but demonstrate improved optical stability at elevated temperatures. The efficiency for the pcLEDs also exhibits a similar trend compared to their respective blue LEDs but with a difference in magnitude. This efficiency drop might be attributed to a number of factors; (i) increased non-radiative recombination processes and increased leakage currents in the quantum wells of the LEDs, (ii) phosphor quenching and (iii) increase of transmission loss in the silicone [7, 10, 11]. After blue light is emitted out of the LED, two types of losses could occur within the package: Stokes energy loss and package-related losses. Stokes loss is determined by the amount of down-conversion processes in the phosphor particles while package-related loss is due to light scattering and absorption losses. Light scattering may occur within the phosphor particles or in the packaging material. On the other hand, the emitted light from the LED and phosphor particles can be (re-)absorbed by the surfaces of the LED device, phosphor particles, and its packaging materials. These aggregations of losses are termed as light extraction losses. The light extraction losses for both die-bonding configurations were found to increase with lower CCT value. As shown in Fig. 2, the radiant efficiency for the conventional bonded and flip-chip bonded LEDs dropped to ~32% and ~23% respectively at CCT value of 2700 K. Since the packaging material and physical construction of the package are similar, the efficiency difference between the various CCT ratings is assumed to be attributed mainly to the phosphor layer.

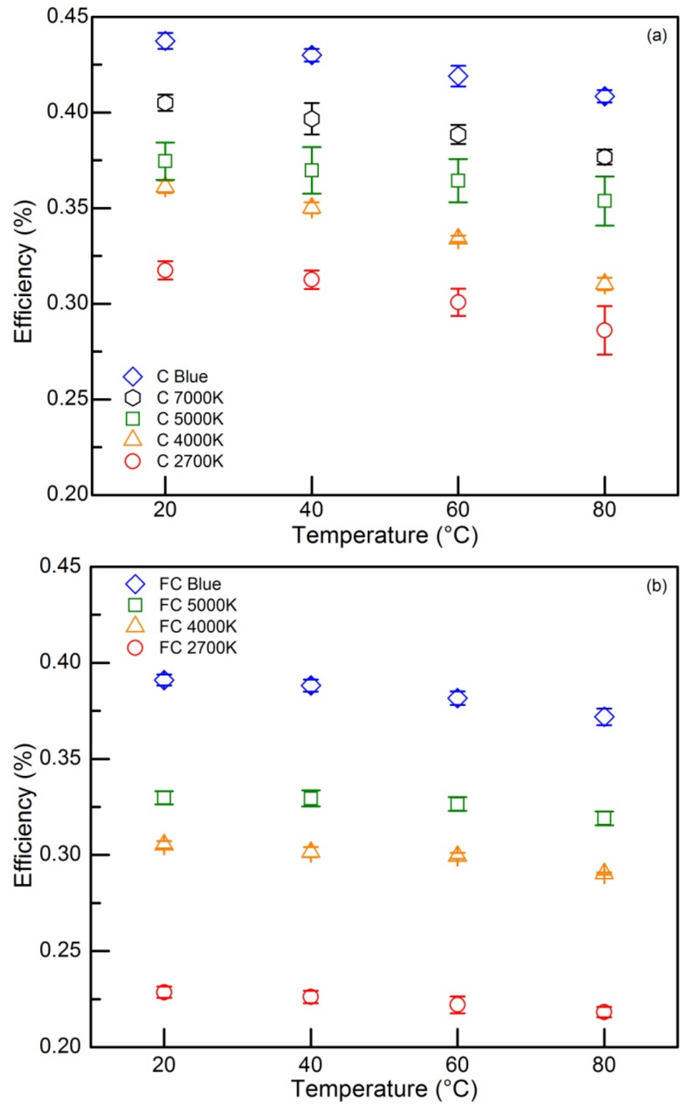

Fig. 2. Radiant efficiency of (a) conventional and (b) flip-chip bonded LEDs. Radiant efficiency reduces with respect to higher operating temperatures for all the CCT values.

In a pcLED package, the light emitted from the package is determined by both the LED device and the phosphor layer. To study the light extraction losses contributed by the phosphor layer, the blue (LED) and yellow (phosphor) light outputs are computed separately as yellow-blue (Y-B) ratio. Typically, a low CCT value would yield a high Y-B ratio due to a higher proportion of yellow light emission and vice versa. Generally, the Y-B ratio was observed to reduce with temperature for all the CCT values as shown in Fig. 3. The reduction of Y-B ratio at elevated temperature is assumed to be caused by the lower phosphor conversion efficiency. However, the Y-B ratio decay rate increases with higher CCT values for both conventional and flip-chip bonded LEDs, implicating that a thicker phosphor layer or a higher phosphor concentration increase the amount of light extraction losses. It is also possible that the different phosphor species used in the 2700 K CCT may cause the change of Y-B ratio due to their different temperature-dependent and optical properties. The lower phosphor conversion efficiency and higher light extraction losses may generate significant self-heating in the phosphor layer and cause the LED junction temperature to increase.

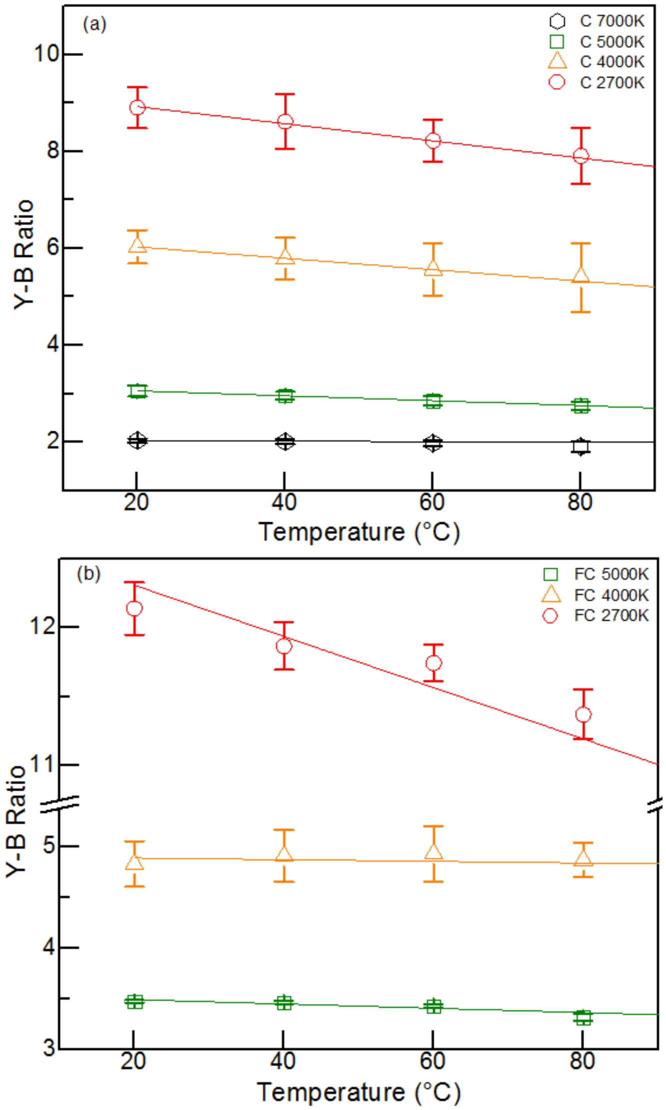

Fig. 3. Yellow-Blue ratio of (a) conventional and (b) flip-chip bonded LEDs. Significant Y-B ratio shift was observed for the 2700 K CCT as compared to the remaining CCT values.

B. Thermal Characterization

To understand the implication of light extraction losses on the thermal response of the LED package, the junction temperature of the LED has been approximated using the electrical forward voltage method. The temperature rise is the temperature difference between the LED's junction temperature with respect to the operating temperature. Both conventional and flip-chip bonded pcLEDs exhibit the same characteristics of a higher temperature rise with decreasing CCT as shown in Fig. 4. This phenomenon is attributed to 2 main factors; (i) low phosphor quantum efficiency, which induces phosphor self-heating, (ii) light absorption losses in the phosphor layer. As the phosphor thickness or concentration in the phosphor layer increases, higher amount of light scattering and absorption losses could occur. Together, these factors will exacerbate the heat load in the package, leading to significant temperature increase. This is clearly demonstrated for both sets of LEDs where the temperature rise increase by as much as ~2.6 times and ~1.4 times at 2700 K CCT for the conventional bonded and flip-chip bonded LEDs, respectively. This temperature rise has a direct impact on the thermal resistance value since thermal resistance is derived from it and is shown in Fig. 5. A higher temperature rise will typically lead to a higher thermal resistance value and this means more heat accumulation and a larger temperature gradient exists within the package.

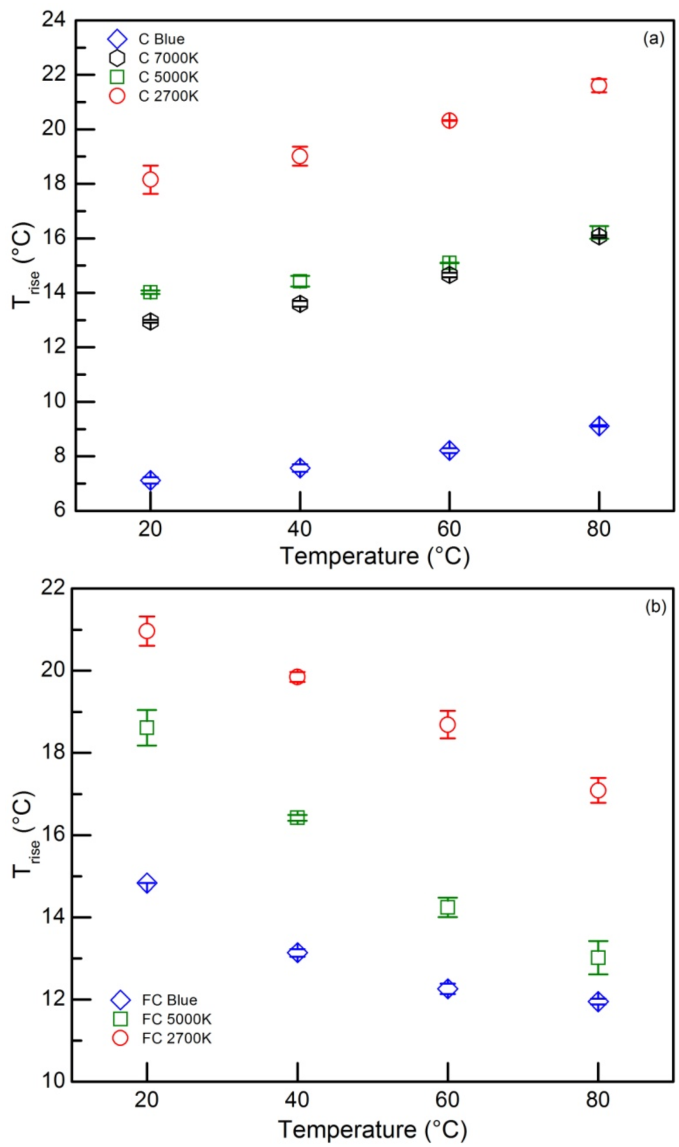

Fig. 4. Temperature rise of (a) conventional and (b) flip-chip bonded LEDs. Conventional bonding exhibits an upward temperature rise trend whereas flip-chip bonding can readily reduce the temperature rise due to its improved heat dissipation capabilities.

For the conventional bonded LEDs, an upward temperature rise and thermal resistance trend is observed as the operating temperature increases. This means that the conventional bonded LEDs experience more heat accumulation within the package as the operating temperature increases. However, the flip-chip bonded LEDs showed an opposite downward response. This is in spite of the fact that a higher operating temperature will increase the amount of non-radiative recombination processes, leading to even higher heat flux generation in the LED package. The differing temperature rise or thermal resistance trend is attributed to its packaging architecture since the heat accumulated in the package depends not only on the heat generated by the LED device itself, but also on its heat dissipation capabilities.

It is worth noting that manufacturers currently report a fixed thermal resistance value for all CCT values under a fixed operating temperature. However, it was found that the thermal resistance depends on the CCT values as well as operating temperature. Inaccurate LED metrics reporting can be detrimental as overexposure to high temperature can adversely affect the lumens performance and service life of the LED package [12].

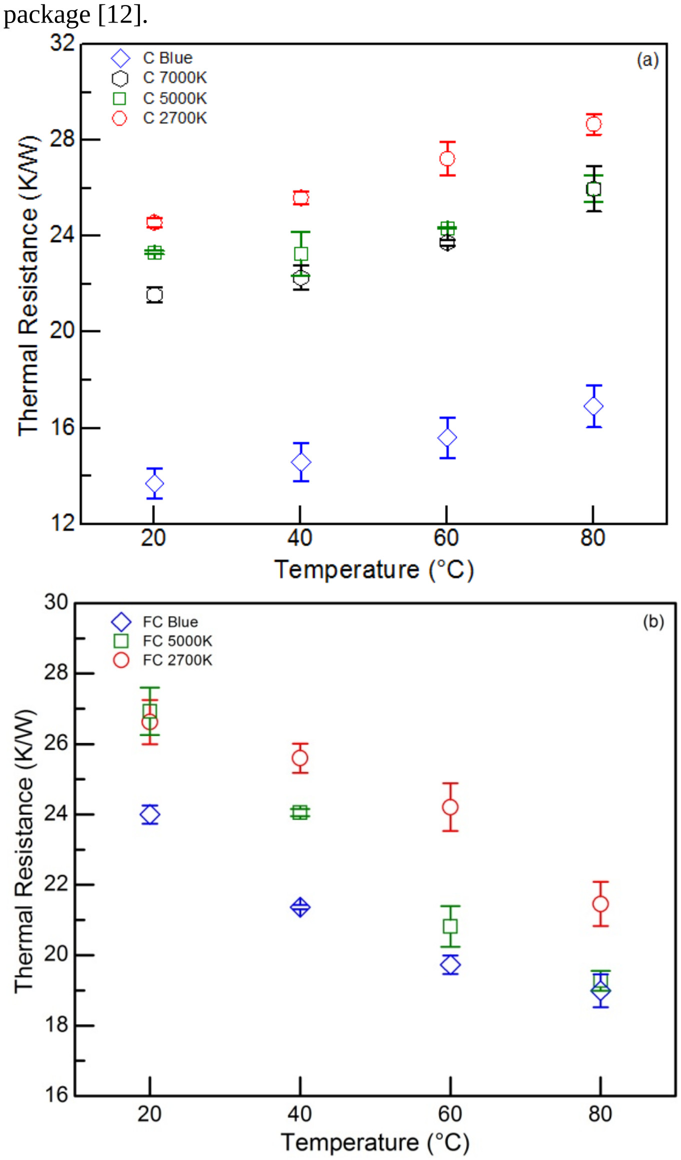

Fig. 5. Real thermal resistance of (a) conventional and (b) flip-chip bonded LEDs at different operating temperatures.

IV. Discussion

Although flip-chip bonding offers a more effective heat dissipating capability as compared to conventional bonded LEDs, the flip-chip bonded LEDs exhibit a slightly lower optical efficiency than the conventional bonded LEDs for all the CCT values. It is postulated that the flip-chip bonded LEDs have a higher total internal reflection (TIR) within the LED structure. For an effective comparison between the different die-bonding configurations, the total light extraction losses due to light scattering and absorption losses are computed with reference to their corresponding blue emitting LEDs and the normalized optical efficiency is depicted in Table II. A higher phosphor concentration or a thicker phosphor layer increases the light trapping efficiency due to the higher probability of the blue light emitting from the LED interacting with the phosphor particles. The trapping of light lowers the light output substantially and causes higher heat generation. At 2700 K CCT, the flip-chip bonded LEDs exhibit a normalized optical efficiency of about 59% whereas conventional bonded LEDs have a higher efficiency of 74% as compared to their respective blue emitting LEDs. The higher light extraction loss for the flip-chip bonded LEDs is attributed to the higher amount of light scattering and back reflection of light from the high phosphor particle concentration in the phosphor layer. This finding substantiate Tran et al. [1]'s simulations that a thicker phosphor layer with lower concentration of phosphor particles can reduce the amount of light extraction losses. However, a lower light extraction loss does not translate to a lower temperature rise. In the case of the conventional bonded LEDs at 5000 K CCT, a low light extraction loss of about 12% can cause the LED junction temperature to increase by almost 2 times as compared to its blue LEDs. In comparison to the flip-chip bonded LEDs at the same CCT values, a 15% light extraction losses only constitute to a 1.3 times increase of junction temperature.

TABLE II
Normalized Optical Comparison of LED Packages under Different Light Emission Properties

Color	Conventional bonding/phosphor thickness variation			Flip-chip bonding/phosphor concentration variation		
	Efficiency	T_{rise} (°C)	T_{rise} (relative)	Efficiency	T_{rise} (°C)	T_{rise} (relative)
Blue	100%	7.1	1X	100%	14.8	1X
7000K	93%	12.9	1.8X			
5000K	88%	14.0	2.0X	85%	18.6	1.3X
2700K	74%	18.2	2.6X	59%	20.9	1.4X

When heat is generated in a material, i.e. LED device or phosphor particles, heat will accumulate in the material and the extent of temperature rise depends on the thermal properties of itself as well as the heat dissipating means within the package. Analogous to an electrical circuit, the heat flow path depends on the thermal conductivity of its materials and contact thermal resistance between adjoining materials. A thin and high thermal conductive material will transfer heat fluxes more effective than a thick and poor thermal conductor. For the blue emitting LED, the top surface of the LED device is exposed to air, which has much poorer thermal properties as compared to the packaging materials such as phosphors, silicone etc. Hence, the bulk of the heat generated in the LED device is dissipated downwards through the LED package. When phosphor is deposited over the LED, the additional heat source(s) from the phosphor layer increases the LED junction temperature. The physical presence of the phosphor layer and the packaging materials allow possible heat flow paths from the top of the LED package. Hence, to analyze the influence of the phosphor layer on the thermal response in the LED package, structure function evaluation of the blue LEDs and their corresponding pcLED packages were computed. Heat accumulation and the change of heat flow paths within the LED package are identified by analyzing the change of transient thermal response. In the case of the conventional bonded LEDs (see Fig. 6(a)), heat accumulation are observed from the merging of structure function peaks, which is the separation point between two thermally contrasting materials. As the phosphor thickness increases, the heat generated at the LED and phosphor layer intensifies due to the low phosphor quantum efficiency in addition to higher light extraction losses. The heat accumulation at the LED-phosphor layer region gradually converges and, at a low CCT rating of 2700 K, the heat flux generated by both the LED and phosphor layer dominate such that the thermal interfaces at the LED-phosphor layer region became indistinguishable. It was also possible that the heat generated in the phosphor layer first dissipated upwards and around the LED chip and then subsequently onto the AlN substrate.

As illustrated in Fig. 6(a), the heat generated by the GaN LED device is transferred to the AlN substrate through the thick sapphire material. Due to the poor intrinsic thermal conductivity of the sapphire material ($K_{Al_2O_3}$ ~46 W/m·K), there is significant heat accumulation within the GaN LED device. As such, the conventional bonded LEDs exhibit an upward temperature trend. On the other hand, flip-chip bonding allows effective heat transfer onto the AlN substrate due to the high thermal conductivity of the gold bumps (K_{Au} ~318 W/m·K). The heat generated by the LED is transferred effectively to the AlN substrate. Hence, the high optical loss in flip-chip bonded pcLEDs does not cause any significant changes to its thermal paths and merely exhibits a shift of partial thermal resistances in the structure function evaluation as compared to its blue LEDs (see Fig. 6(b)). This shows that almost all the heat fluxes generated in the LED dissipated through the Au bumps and reinstates the fact that the packaging architecture has a significant influence on the temperature rise and thermal resistance of the package.

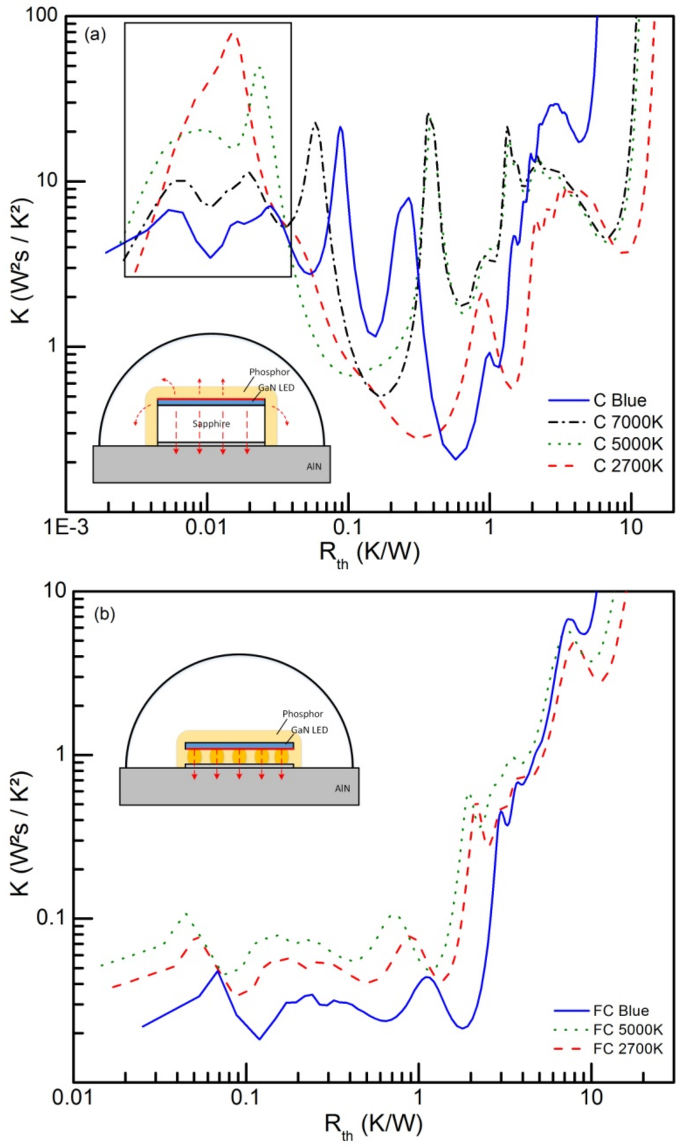

Fig. 6. Derivative structure function of (a) conventional and (b) flip-chip bonded LEDs at 20 °C. Heat accumulation at the phosphor-LED region can be observed when the phosphor layer thickens for the conventional bonded pcLEDs.

V. Conclusion

This paper highlights the impact of phosphor concentration and thickness on both the photometric and colorimetric qualities of conformal phosphor coated LEDs and the subsequent thermal effects with different bonding configurations. It has been shown in this paper that white light emission with various color qualities can be attained by varying the phosphor particle concentration or thickness of the phosphor layer in a pcLED package. A thicker phosphor layer and a higher phosphor particle concentration increases the amount of light trapping due to light scattering and back reflection of light. The light extraction losses in the phosphor layer induce heat accumulation at the phosphor layer and increase the temperature and thermal resistance in the LED package. Hence, the thermal resistance of the LED package changes with the CCT values. However, the temperature rise and thermal resistance can be reduced with a flip-chip die-bonding configuration where the heat generated in the LED chip and phosphor layer is dissipated effectively onto the AlN substrate. This is verified by observing the thermal paths in the structure function evaluation of both flip-chip and conventional die-bonding configurations. As the thermal resistance of the LED package is found to change with different operating temperatures, CCT values and die-bonding configurations, there is a need to provide detailed thermal information for different LED packages. Insufficient or inaccurate reporting of thermal data may change the photometric and colorimetric properties of the white light emitted from the LED package.

REFERENCES

[1] Tran, N.T. and F.G. Shi, Studies of Phosphor Concentration and Thickness for Phosphor-Based White Light-Emitting-Diodes. J. Lightwave Technol., 2008. 26(21): p. 3556-3559.

[2] Tran, N.T., J.P. You, and F.G. Shi, Effect of phosphor particle size on luminous efficacy of phosphor-converted white LED. Lightwave Technology, Journal of, 2009. 27(22): p. 5145-5150.

[3] Tran, N.T., C.G. Campbell, and F.G. Shi, Study of particle size effects on an optical fiber sensor response examined with Monte Carlo simulation. Applied optics, 2006. 45(29): p. 7557-7566.

[4] Min, H. and Y. Liyu, Heat Generation by the Phosphor Layer of High-Power White LED Emitters. Photonics Technology Letters, IEEE, 2013. 25(14): p. 1317-1320.

[5] Dal Lago, M., et al., Phosphors for LED-based light sources: Thermal properties and reliability issues. Microelectronics Reliability, 2012. 52(9–10): p. 2164-2167.

[6] Luo, X., et al., Phosphor self-heating in phosphor converted light emitting diode packaging. International Journal of Heat and Mass Transfer, 2013. 58(1–2): p. 276-281.

[7] Bohan, Y., et al., Can Junction Temperature Alone Characterize Thermal Performance of White LED Emitters? Photonics Technology Letters, IEEE, 2011. 23(9): p. 555-557.

[8] Lin, C.C. and R.-S. Liu, Advances in Phosphors for Light-emitting Diodes. The Journal of Physical Chemistry Letters, 2011. 2(11): p. 1268-1277.

[9] Chen, L., et al., Light converting inorganic phosphors for white light-emitting diodes. Materials, 2010. 3(3): p. 2172-2195.

[10] Bachmann, V., C. Ronda, and A. Meijerink, Temperature Quenching of Yellow Ce3+ Luminescence in YAG:Ce. Chemistry of Materials, 2009. 21(10): p. 2077-2084.

[11] Zhang, Q., et al., Effect of temperature and moisture on the luminescence properties of silicone filled with YAG phosphor. Journal of Semiconductors, 2011. 32(1): p. 012002.

[12] Chang, M.-H., et al., Light emitting diodes reliability review. Microelectronics Reliability, 2012. 52(5): p. 762-782.